

MARSHALL MIX DESIGN IN LINE WITH THE NIGERIAN GENERAL SPECIFICATIONS (ROAD AND BRIDGES)

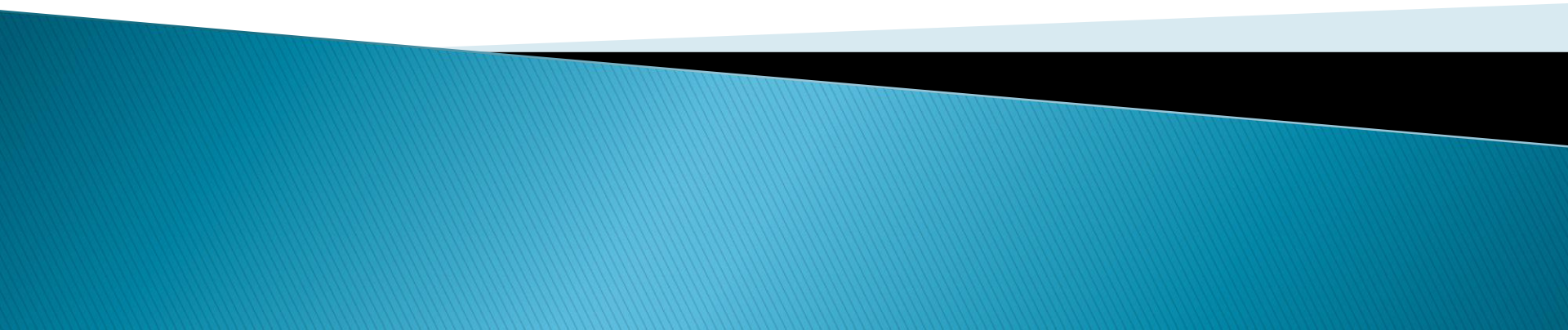
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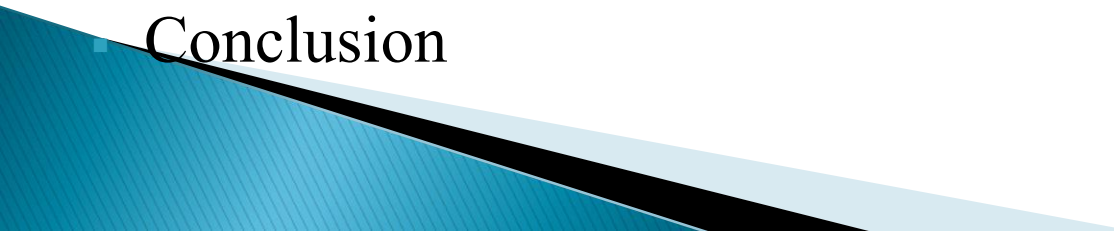
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**International Workshop on Global Trends in Designs
and Construction of Durable Road Pavements**

Nigerian Building and Road Research Institute



Outline

- Introduction
 - Design of Asphalt Mixtures
 - Marshall Mix Design
 - ❖ Selection of materials (aggregates and bitumen)
 - ❖ Determination of the specific gravity of the aggregates and bitumen
 - ❖ Preparation of the specimens
 - ❖ Determination of the bulk specific gravity and theoretical specific gravity of the mix
 - ❖ Determination of the stability and flow
 - ❖ Density/Specific gravity and voids analysis (Volumetric characteristics)
 - ❖ Establishing the job mix
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- 

Introduction

A bituminous/asphalt mixture includes bituminous materials (binders), properly graded aggregates, and additives. Bituminous/asphalt mixtures are used mainly in the surface layer of road and airfield pavements.

Three main types of aggregates used in bituminous mixtures are:

- Coarse aggregate (CA): A portion of the aggregate retained on the No. 5 mm opening sieve and shall be hard, clean, and durable crushed igneous rock. The crushed stone shall be free from dirt or other objectionable matter (FMPWH, 2016)
- Fine aggregate (FA): A portion of the aggregate passing the No. 5 mm opening sieve and shall be quarry fines produced from the crushing of igneous rock. They shall be composed of clean, tough, rough-surfaced, and angular particles, free from lumps, or balls of clay, loam, and other deleterious substances (FMPWH, 2016).
- Mineral filler. Finely ground particles of hydrated lime, Portland cement, or other non-plastic mineral matter approved by the Engineer. It shall be free from foreign or other objectionable materials and shall meet the requirements shown in Table 1 (FMPWH, 2016):

Introduction

Table 1: Requirements for mineral filler

Sieve size	% by weight passing
300 μm	100
200 μm	95-100
75 μm	85-100

The asphalt mixtures used for the construction of road pavements (flexible) are:

- ❖ Asphalt Concrete (AC);
- ❖ Stone Mastic Asphalt (SMA);
- ❖ Hot Rolled Asphalt (HRA); and
- ❖ Porous Asphalt (PA).

The most commonly used bituminous mixture in Nigeria is asphalt concrete.

Introduction

Asphalt concrete: A high-quality, dense-graded hot mix asphalt mixture. Asphalt concrete is a composite material commonly used to surface roads, parking lots, and airports. It is specified in the General Specification, Roads and Bridges (FMPWH, 2016) and British Standard (BS EN13108-1, 2016)

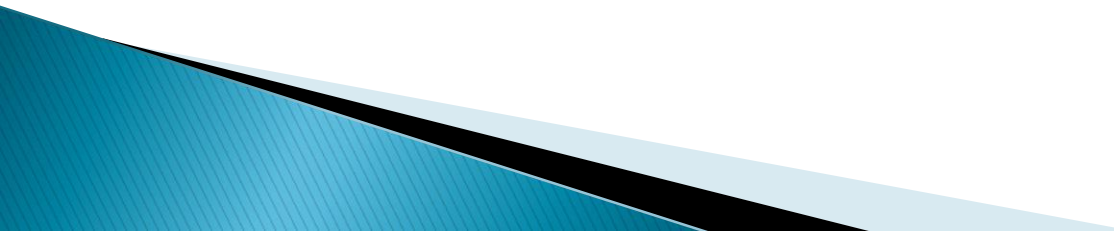
Stone Mastic Asphalt: A special mixture with improved rutting resistance and increased durability. SMA mixtures are designed to have a high coarse aggregate content (typically 70–80%), a high binder content (typically over 6%), and a high filler content (typically about 10%). SMA offers superior noise reduction compared to asphalt concrete. Bitumen modified with polymers and/or fibers are typically used. It is specified in British Standard (BS EN 13108-5, 2016,).



Introduction

Hot rolled Asphalt: A gap-graded bituminous mixture. It is essentially a bitumen/fine aggregate/filler mortar into which some coarse aggregate is placed. The mechanical properties are dominated by those of mortar. It has been used extensively as the wearing course on major roads in the United Kingdom. The coarse aggregate content is low (typically 30%), which results in the compacted mixture having a smooth surface. It is specified in the British Standard (BS EN13108-4, 2016).

Porous Asphalt: This is a uniformly graded material that is designed to provide large air voids so that water can drain to the verges within the layer thickness. Thick binder films are required to resist water damage and ageing of the binder. It is specified in British Standard (BS EN 13108-7, 2006).



Design of Asphalt Mixtures

Asphalt mixtures are designed to ensure that the resulting pavement can resist fatigue, permanent deformation, low-temperature cracking (cold areas), and moisture-induced damage. Also, they must possess good durability and adequate skid resistance.

The mix design process combines aggregates and asphalt binder to meet project requirements and determine the optimum binder content.

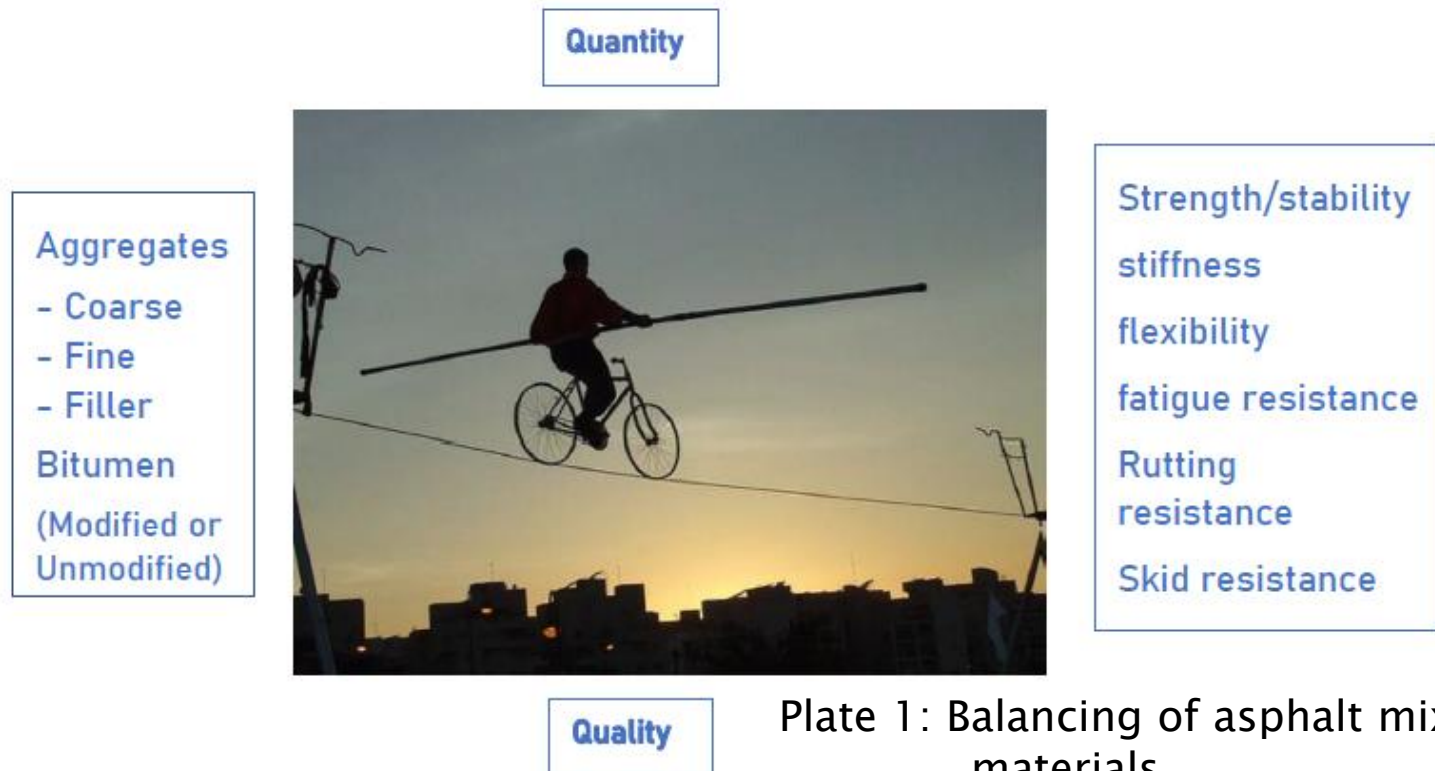


Plate 1: Balancing of asphalt mixtures materials

Marshall Mix Design

The General Specification (Roads and bridges) specified the use of the Marshall mix design to establish the job mixes for asphalt mixtures.

The Marshall Method of mix design involves:

- ❖ selection of the materials (aggregates and bitumen)
- ❖ determination of the specific gravity of materials
- ❖ the preparation of test specimens;
- ❖ Determination of the bulk specific gravity and theoretical specific gravity of bituminous mix;
- ❖ Determination of the stability (stability) and flow (flexibility) of the prepared samples
- ❖ the density and voids analysis (volumetric characteristics) and
- ❖ Establishing the job mix

Marshall Mix Design

Selection and grading of the aggregates and bitumen

Appropriate aggregates (fine and coarse) and mineral filler required to ensure the blend of the aggregates falls within the specified envelope (Table 2) are selected based on their shape and size and the gradations are determined.

Two types of courses: wearing and binder courses are specified in the General Specifications (Roads and Bridges) (FMPWH, 2016).

The pavement design will normally indicate whether only wearing course or both are needed.

The proportioning of the aggregates is usually done by trial-and-error method based on experience. Different percentages of the aggregates will be selected and checked to fall within the envelope.

The specifications for the aggregates and the asphalt concrete mixture are shown in Tables 3 and 4

Marshall Mix Design

Selection and grading of the aggregates and bitumen (cont'd)

Table 2: Grading envelope for asphaltic concrete binder and wearing courses (FMPWH, 2016)

	% by Weight Passing	
Sieve Size	40 mm – 65 mm Binder Course	40 mm – 65 mm Wearing Course
31.8 mm	100	100
25 mm	90 - 100	100
19.0 mm	70 - 90	100
12.5 mm	55 - 80	85 - 100
9.5 mm	47 - 70	75 - 92
6.4 mm	40 - 60	65 - 82
2.8 mm	27 - 45	50 - 65
1.25 mm	20 - 34	36 - 51
600 µm	14 - 27	26 - 40
300 µm	8 - 20	18 - 30
150 µm	5 - 15	13 - 24
75 µm	2 - 7	7 - 14
Bitumen Content (% by weight of aggregate)	4.5 - 6.5	5 - 8.0

Marshall Mix Design

Selection and grading of the aggregates and bitumen (cont'd)

Table 3: Aggregate Specifications for Dense Bitumen Macadam and Asphaltic Concrete Wearing and Base Courses (FMPWH, 2016)

Pavement Course	Aggregate Crushing Value	Flakiness Index	Absorption Factor
Dense Bitumen Macadam Base	30	35	1.5
Dense Bitumen Macadam Wearing Course	30	35	0.5
Asphaltic Concrete Base	30	35	0.5
Asphaltic Concrete Wearing Course	30	35	0.5

Table 4: Specification for Asphalt concrete mixtures (FMPWH, 2016)

Property	Base course	Wearing course
Optimum binder content	4.5% - 6.5%	5.0% - 8.0%
Stability. Not less than	3.5 kN	3.5 kN
Flow	2 mm – 6 mm	2 mm – 4 mm
Voids in total mixture	3% - 8%	3% - 5%
Voids filled with bitumen	65% - 72%	75% - 82%

Marshall Mix Design

Selection and grading of the aggregates and bitumen (cont'd)

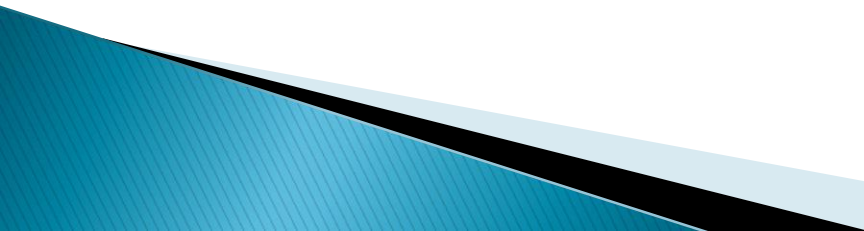
The bitumen grades specified in the General Specifications (Roads and Bridges) are the 60/70 and 80/100 penetration grades (Table 5). Although, the 60/70 penetration grade is commonly used.

The bitumen will be selected and subjected to consistency tests like the penetration, softening point, and viscosity tests. It must meet the specifications.

Determination of the specific gravity of the aggregates and bitumen

Laboratory tests are conducted to determine the specific gravity of the aggregates and bitumen.

The values are required in calculating the volumetric characteristics of the mixture.



Marshall Mix Design

Table 5: Quality of Bitumen (FMPWH, 2016)

Property	Asphalt Cement (Bitumen)	
	80 – 100 Pen	60 – 70 Pen
Specific gravity at 25°C	1.00 – 1.05	1.01 – 1.06
Softening point at °C	45 - 52	48 - 56
Penetration at 25°C ...0.1 mm	80 -100	60 – 7-
Density at 25 °C cm minimum	100	100
Minimum loss on heating for 5 hours at 163°C by weight max	0.5	0.2
Solubility in CS ₂ % by weight ... min	99	99
Drop in penetration after heating % original ... max	20	20
Flash point (open cut) at °C min	225	250
Ash % by weight ... max	0.5	0.5

Marshall Mix Design

Preparation of the specimens

The samples for the stability and flow test are prepared after establishing the aggregate gradations and achieving the right proportioning of the aggregates such that the curve falls within the envelope and selecting the appropriate bitumen.

This involves mixing the heated aggregates (120 to 149°C) and asphalt binder (135 to 163°C) in precise proportions and compacting the mixture into cylindrical specimens using a specialized Marshall compactor. The samples are given 35, 50 or 75 blows at the top and bottom for light, medium or heavy trafficked road, respectively.

Marshall test specimens (Plate 2) are typically cylindrical samples with a diameter of 101.6 mm (4 inches) and a height of 63.5 mm (2.5 inches).



Plate 2: Marshall Specimens/samples

Marshall Mix Design

The automatic compactor and the specimen extractor are shown in Plates 3 and 4, respectively.



Plate 3: Automatic compactor



Plate 4: Specimen Extractor

Marshall Mix Design

Determination of the bulk specific gravity and theoretical specific gravity of bituminous mix:

The bulk specific gravity or the actual specific gravity of the mix G_m is calculated as shown in equation 1:

$$G_m = \frac{W_m}{W_m - W_w} \quad (1)$$

where, W_m is the weight of the mix in air

W_w is the weight of the mix in water.

Note that $W_m - W_w$ gives the volume of the mix.

Sometimes to get accurate bulk specific gravity, the specimen is coated with thin film of paraffin wax, when weight is taken in the water. However, this requires considering the weight and volume of wax in the calculations.

Marshall Mix Design

Determination of the bulk specific gravity and theoretical specific gravity of asphalt mix:

The theoretical specific gravity G_t is calculated as shown in Equation 2

$$G_t = \frac{W_1 + W_2 + W_3 + W_b}{\frac{W_1}{G_1} + \frac{W_2}{G_2} + \frac{W_3}{G_3} + \frac{W_b}{G_b}} \quad (2)$$

where W_1 is the weight of coarse aggregate in the total mix,
 W_2 is the weight of fine aggregate in the total mix,
 W_3 is the weight of filler in the total mix,
 W_b is the weight of bitumen in the total mix,
 G_1 is the apparent specific gravity of coarse aggregate,
 G_2 is the apparent specific gravity of fine aggregate,
 G_3 is the apparent specific gravity of the filler and
 G_b is the apparent specific gravity of the bitumen.

Marshall Mix Design

Determination of the stability and flow

The Marshall stability and flow test is conducted on the specimens.

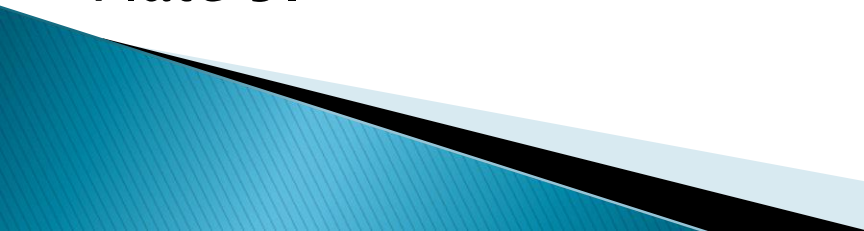
Marshall stability measures the maximum load the asphalt concrete specimen can withstand before failure at 60°C.

It indicates the mixture's resistance to deformation and the ability to support traffic loads.

The Marshall flow test measures the deformation the asphalt concrete specimen undergoes under the maximum load and gives insight into the mixture's flexibility

The values are adjusted using the correction factor.

The Marshall stability and flow testing machine is shown in Plate 5.



Marshall Mix Design



Plate 5: Marshall stability and flow testing machine

Marshall Mix Design

Volumetric characteristics of asphalt mixtures

The phase diagram of the asphalt mix expressing the volumetric features is shown in Figure 1.

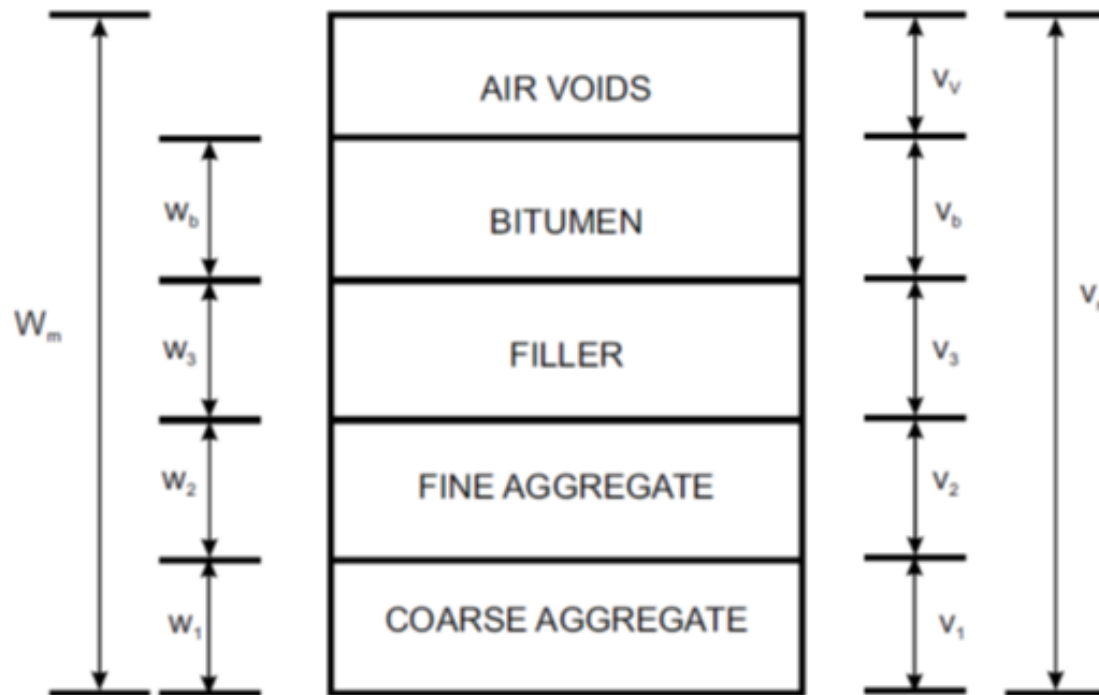


Figure 1: Phase diagram of asphalt mix

Marshall Mix Design

Volumetric characteristics of asphalt mixtures

Air voids

The air voids in a paving mixture (see Figure 1) are small pockets of air between the bitumen-coated aggregate particles.

A certain percentage of air voids is necessary for the finished hot mix asphalt (HMA) to allow for additional compaction under traffic and a slight amount of asphalt expansion because of temperature increases.

The durability of an asphalt pavement is a function of the air void content.

The values of 3%-8% and 3%-5% are specified for binder and wearing courses, respectively (FMPWH, 2016).

Air voids V_v is the percent of air voids by volume in the specimen is calculated as shown in Equation 3:

$$V_v = \left(\frac{G_t - G_m}{G_t} \right) \times 100 \quad (3)$$

where G_t is the theoretical specific gravity of the mix and G_m is the bulk or actual specific gravity of the mix.

Marshall Mix Design

Volumetric characteristics of asphalt mixtures

Voids in the mineral aggregate:

Space between aggregate particles occupied by air and asphalt binder. This is critical for ensuring sufficient binder coverage and adequate durability.

Voids in the mineral aggregate (VMA) must remain high enough to achieve an adequate bitumen film thickness, which results in durable asphalt pavement.

VMA is calculated as the sum of the percent air voids and percent bitumen content in the mixes as shown in Equation 4.

$$VMA = V_v + V_b \quad (4)$$

where V_v is the percent air voids in the mix and V_b is the percent bitumen content in the mix.

Marshall Mix Design

Volumetric characteristics of asphalt mixtures

Voids filled with bitumen:

Percentage of intergranular void space between the aggregate particles (VMA) that contains or is filled with an effective binder (see Figure 1).

VFB is used to ensure proper bitumen film thickness in the mix.

If it is too low, the mix will have poor durability, or if it is too high, the mix can be unstable.

The VFB values specified for asphalt concrete binder and wearing courses are 65 – 72% and 75 -82%, respectively. The VFB is calculated as shown in Equation 5.

$$VFB = \frac{V_b}{VMA} \times 100 \quad (5)$$

where V_b is the percent bitumen content in the mix and VMA is the percent voids in the mineral aggregate.

Marshall Mix Design

Volumetric characteristics of asphalt mixtures

Bitumen content:

The total bitumen content is the amount of bitumen that must be added to the mixture to produce the desired mix qualities.

Aggregate absorption is critical in determining optimum bitumen content.

The volume of bitumen V_b is calculated as shown in Equation 6.

$$V_b = \left(\frac{\frac{W_b}{G_b}}{\frac{W_1 + W_2 + W_3 + W_b}{G_m}} \right) \times 100 \quad (6)$$

where W_1 is the weight of coarse aggregate in the total mix,

W_2 is the weight of fine aggregate in the total mix

W_3 is the weight of filler in the total mix,

W_b is the weight of bitumen in the total mix,

G_b is the apparent specific gravity of bitumen, and

G_m is the bulk specific gravity of mix.

Marshall Mix Design

Establishing the Job Mix

Once the stability and flow values have been determined and the volumetric characteristics calculated, the following graphs shown in Figure 2 will be plotted to determine the optimum bitumen content.

- i. Stability versus bitumen content
- ii. Flow versus bitumen content
- iii. Air voids versus bitumen content
- iv. Voids filled with bitumen versus bitumen content
- v. Voids in mineral aggregate versus the bitumen content

The optimum bitumen content is determined as the average bitumen content corresponding to the bitumen contents at maximum stability, maximum bulk specific gravity, and 4 percent air voids.

$$OBC = \frac{BC \text{ at maximum stability} + BC \text{ at Maximum } G_m + BC \text{ at } 4\% V_V}{3} \quad (7)$$

Marshall Mix Design

Establishing the Job Mix

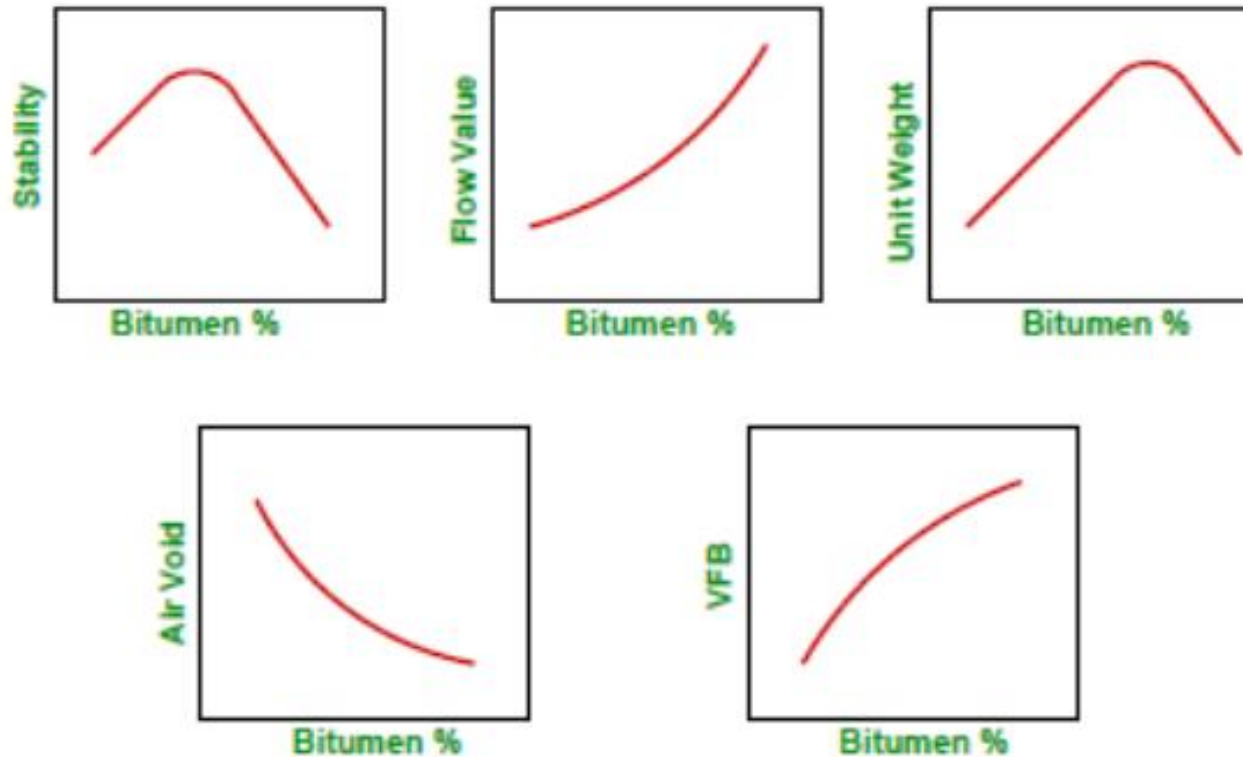


Figure 2: Graphs of Marshall parameters versus bitumen content

Marshall Mix Design

Extraction test

- ❑ The extraction test is essential for quality control. It involves the determination of the bitumen content in the prepared asphalt mixture.
- ❑ This ensures the asphalt mix has the required bitumen (OBC) for stable, durable, and safe pavement with good resistance to rutting and fatigue cracking.
- ❑ The test is carried out following British Standards (BS EN 12697-1, 2012)

$$\text{bitumen content (g)} = \frac{(W_1 - (W_2 + W_3))}{W_1} \quad (8)$$

W_1 = Weight of the sample in grams

W_2 = weight of the extracted aggregates in grams

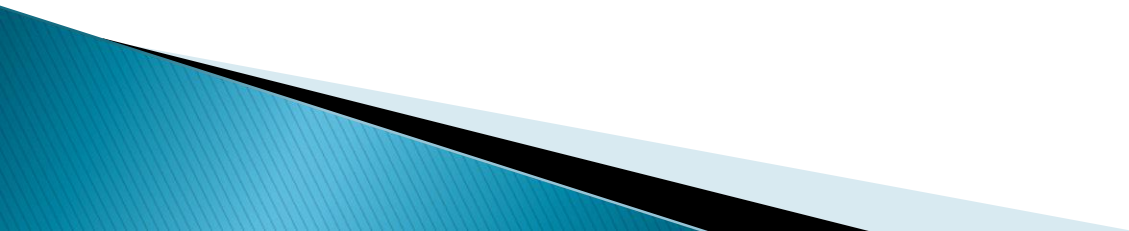
W_3 = weight of the fine aggregate fragments in grams

Case Study

The gradations, weights, and specific gravity of materials and the stability and flow results of the Marshall test conducted on asphalt concrete mix are shown in Tables 6, 7, and 8.

The particle size distribution curves are shown in Figure 3.

Carry out the volumetric analysis and determine the optimum bitumen content.



Case Study

Table 6: Gradations of the aggregates

Size (mm)	¾	19%	½	11%	3/8	17%	Quarry Dust	38%	River sand	15%	Blend	Envelope
19.0	44.4	8.4	100	11	100	17	100	38	100	15	89.4	70-90
12.5	2.1	0.40	41.03	4.51	100	17	100	38	100	15	74.9	55- 80
9.6	1.42	0.27	1.93	0.21	13.4	2.28	100	38	100	15	55.8	47-70
6.3			1.2	0.13	1.79	0.30	97.7	37.1	100	15	52.5	40-60
2.36					1.67	0.28	71.1	27.0	96.9	14.5	41.8	27-45
1.18							53.9	20.5	88.3	13.2	33.7	20-34
0.600							40.0	15.2	65.1	9.8	25.0	14-27
0.300							28.2	10.7	24.0	3.6	14.3	8-20
0.150							14.8	5.6	6.2	0.9	6.5	5-15
0.075							7.6	2.9	1.9	0.3	3.2	2 -7

Case Study

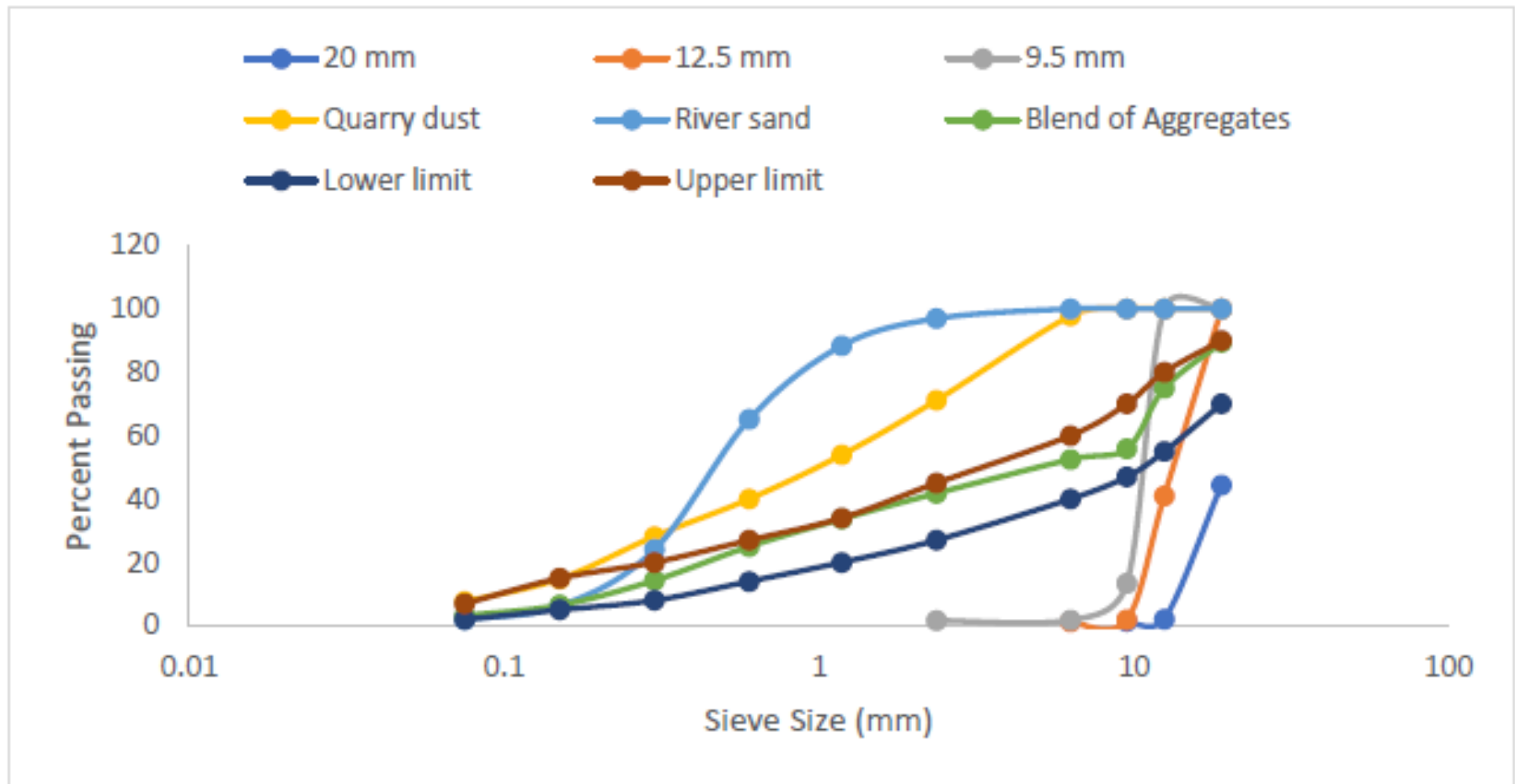


Figure 3: Particle size distribution curves for the aggregates, blends of aggregate and the specified envelope for asphalt concrete (binder course)

Case Study

Table 7: Weight and Specific Gravity of Materials

Bitumen Content (%)	Weight of Coarse Aggregate	Weight of Fine Aggregate	Weight of Filler	Weight of Bitumen	Weight of mix (air)	Weight of mix (Water)
4.5	642	324	180	54	1222	659
5	642	324	180	60	1246	678
5.5	642	324	180	66	1209	673
6	642	324	180	72	1241	698
6.5	642	324	180	78	1210	673
7	642	324	180	84	1232	677
Specific Gravity						
Coarse Aggregate	Fine Aggregate	Filler	Bitumen			
2.80	2.60	1.90	0.98			

Case Study

Table 8: Stability and flow results

Bitumen Content (%)	Uncorrected Stability (kN)	CF	Corrected Stability (kN)	Flow (mm)	Corrected Flow (mm)
4.5	12.552	1.000	12.552	24	6.0
5	13.2	1.000	13.200	23	5.8
5.5	15.064	1.000	15.064	22	5.5
6	17.656	1.000	17.656	20	5.0
6.5	14.712	1.000	14.712	19	4.8
7	11.225	1.000	11.225	17	4.3

Case Study

Solution

Table 9: Summary of the Calculations of volumetric characteristics

% BC	GT	GM	V_v (%)	V_b (%)	VMA (%)	VFB (%)
4.5	2.382	2.171	8.858	9.969	18.827	52.951
5	2.365	2.195	7.188	11.143	18.331	60.788
5.5	2.349	2.256	3.959	12.536	16.495	75.999
6	2.333	2.285	2.057	13.783	15.840	87.014
6.5	2.317	2.253	2.762	14.650	17.412	84.137
7	2.302	2.220	3.562	15.470	19.032	81.284

Case Study

Apparent specific gravity, G_t

$$G_t = \frac{W_1 + W_2 + W_3 + W_b}{\frac{W_1}{G_1} + \frac{W_2}{G_2} + \frac{W_3}{G_3} + \frac{W_b}{G_b}}$$

$$G_t = \frac{642 + 324 + 180 + 54}{\frac{642}{2.80} + \frac{324}{2.60} + \frac{180}{1.90} + \frac{54}{0.98}}$$

$$G_t = \frac{1200}{229.29 + 124.62 + 94.73 + 55.10}$$

$$G_t = \frac{1200}{503.74}$$

$$G_t = 2.382$$

Case Study

Bulk specific gravity, G_m

$$G_m = \frac{W_m}{W_m - W_w}$$

$$G_m = \frac{1222}{1222 - 659}$$

$$G_m = 2.171$$

Air voids (V_v)

$$V_v = \left(\frac{G_t - G_m}{G_t} \right) \times 100$$

$$V_v = \left(\frac{2.382 - 2.171}{2.382} \right) \times 100$$

$$V_v = 8.858$$

Case Study

Bitumen content

$$V_b = \left(\frac{\frac{W_b}{G_b}}{\frac{W_1 + W_2 + W_3 + W_b}{G_m}} \right) \times 100$$

$$V_b = \left(\frac{\frac{54/0.98}{642 + 324 + 180 + 54}}{2.171} \right) \times 100$$

$$V_b = \frac{55.102}{552.741} \times 100$$

$$V_b = 9.969\%$$

Case Study

Voids in mineral aggregate

$$VMA = V_v + V_b$$

$$VMA = 8.858 + 9.969$$

$$VMA = 18.827\%$$

Voids filled with bitumen

$$VFB = \frac{V_b}{VMA} \times 100$$

$$VFB = \frac{9.969}{18.827} \times 100$$

$$VFB = 52.951$$

Case Study

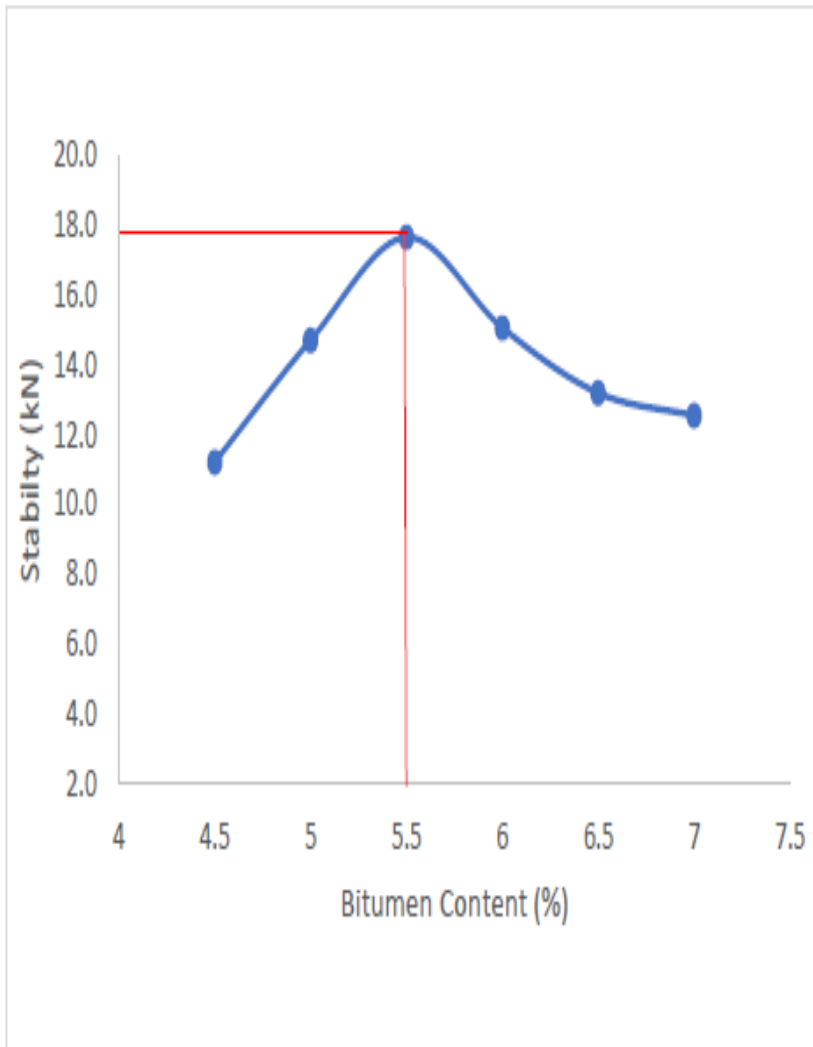


Figure 4: Stability versus the bitumen content

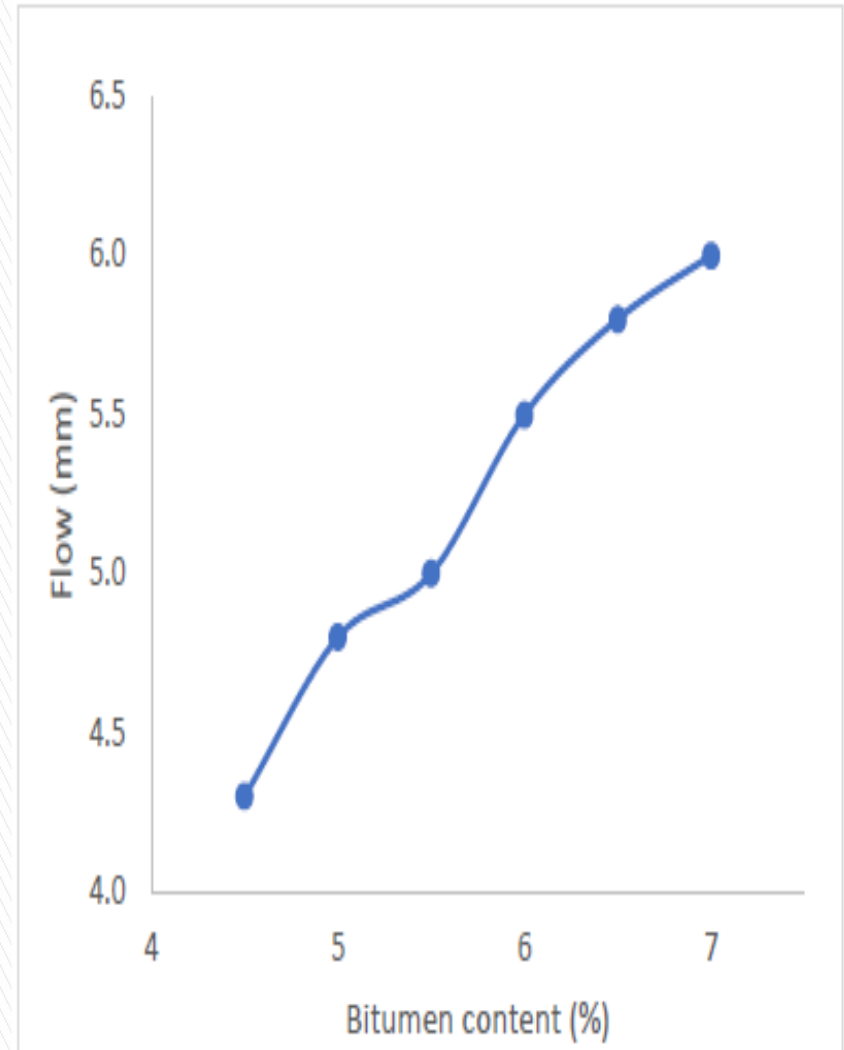


Figure 5: Flow versus the bitumen content

Case Study

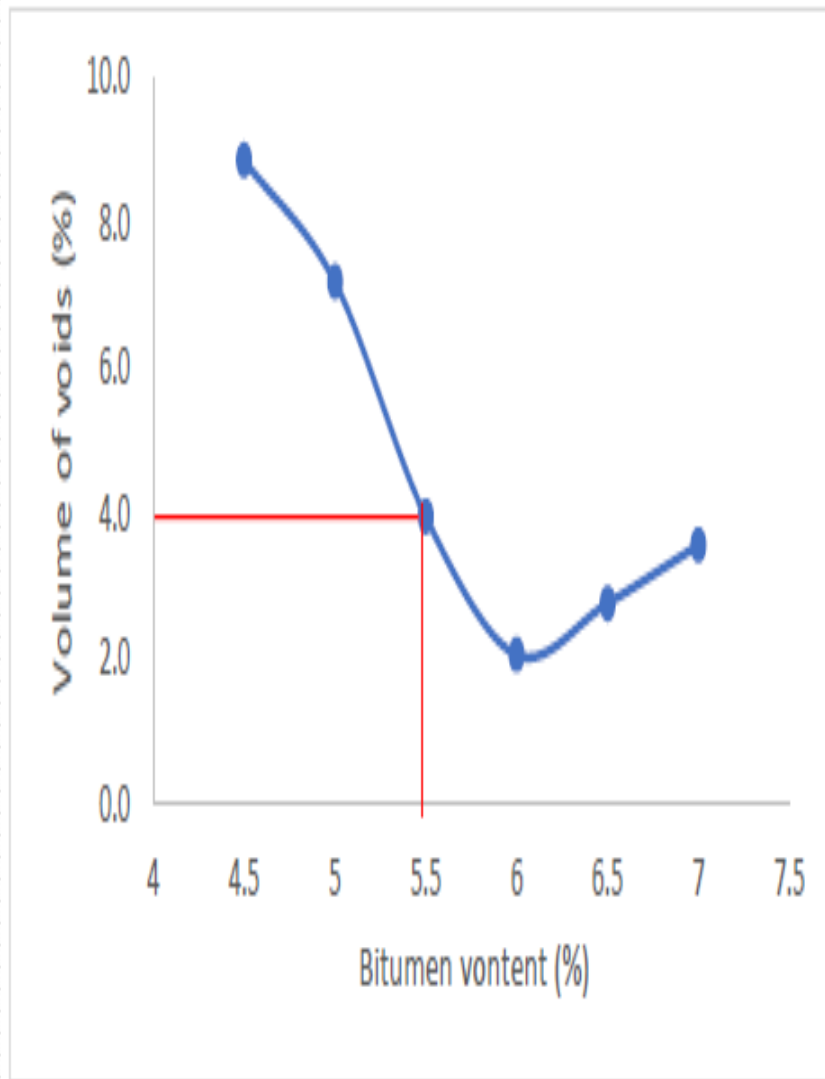


Figure 6: Volume of voids versus the bitumen content

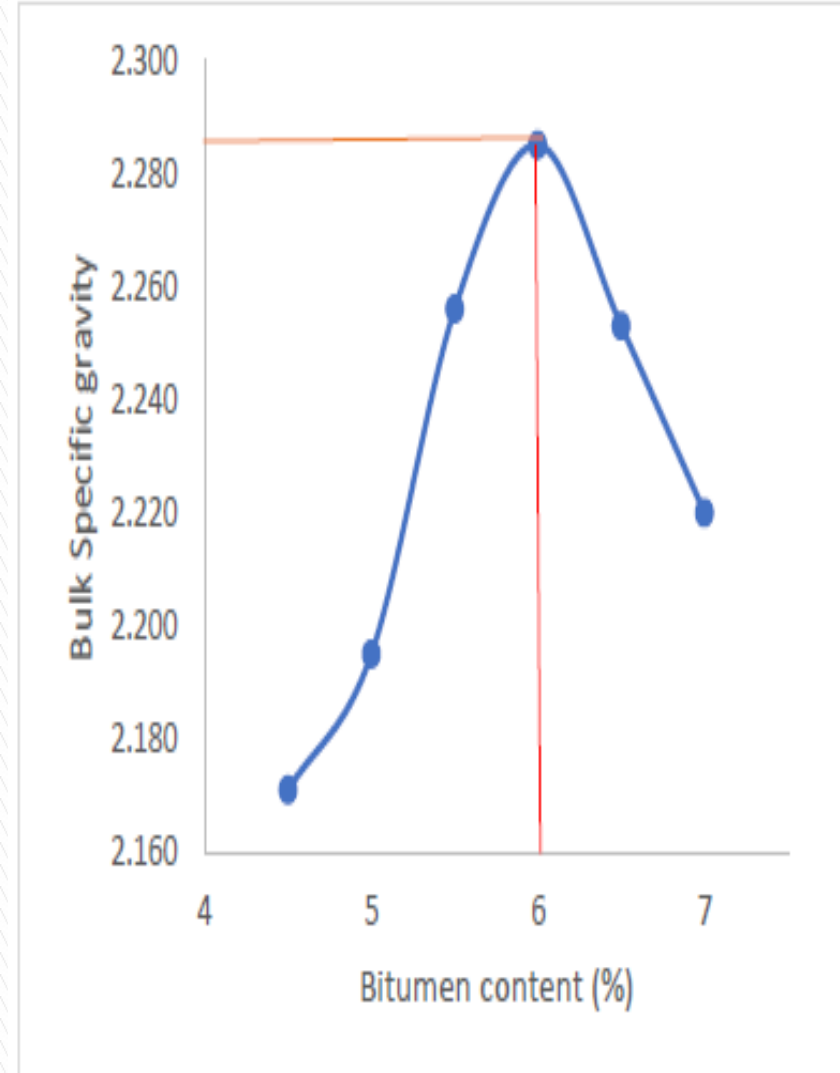
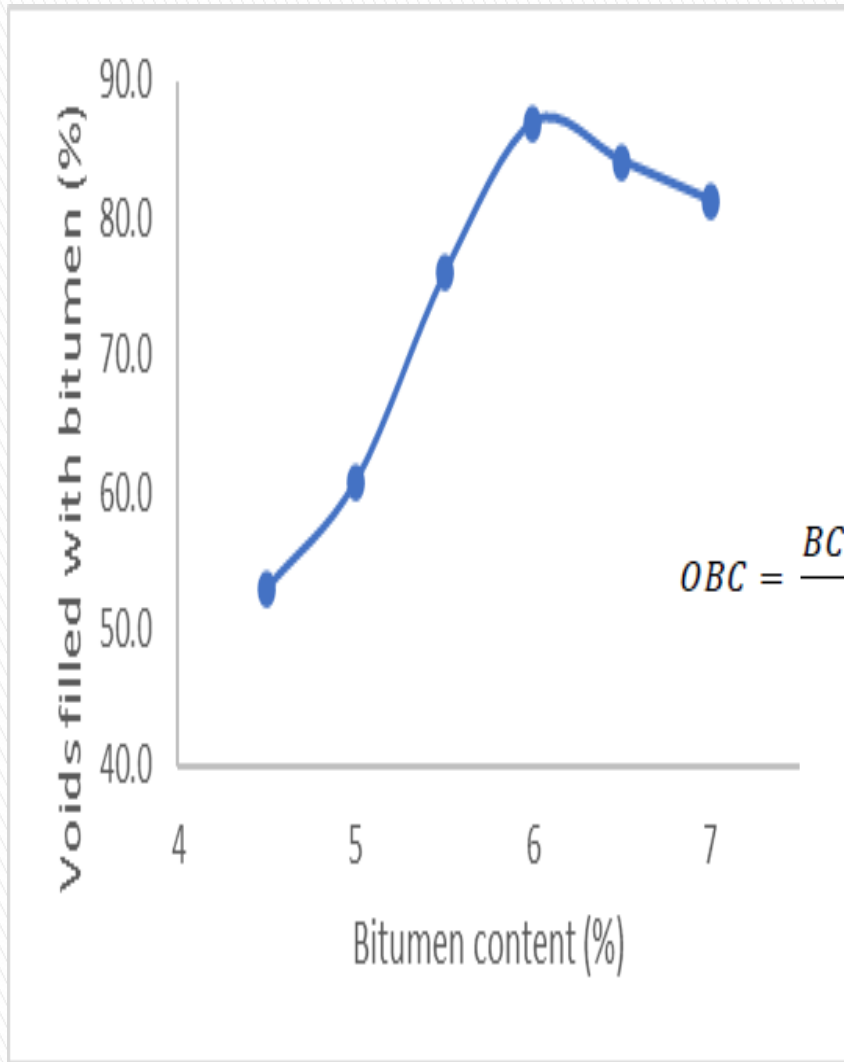


Figure 7: Bulk-specific gravity versus the bitumen content

Case Study



Bitumen content at maximum stability = 5.5 %

Bitumen content at maximum bulk specific gravity = 6%

Bitumen content at 4% air voids = 5.5 %

$$OBC = \frac{BC \text{ at maximum stability} + BC \text{ at Maximum } G_m + BC \text{ at } 4\% V_v}{3}$$

$$OBC = \frac{5.5 + 6.0 + 5.5}{3} = 5.7\%$$

Figure 8: Voids filled with bitumen versus bitumen content

Case Study

Check the values of the stability, flow, air voids, voids with bitumen corresponding to the optimum bitumen content (OBC).

In this case, the OBC is 5.7%

Stability = 17.8 kN

Flow = 4.8 mm

Air voids = 3.6 mm

VFB = 68%

All these values comply with the specifications for asphalt concrete (binder course)

Property	Base course	Wearing course
Optimum binder content	4.5% - 6.5%	5.0% - 8.0%
Stability. Not less than	3.5 kN	3.5 kN
Flow	2 mm - 6 mm	2 mm - 4 mm
Voids in total mixture	3% - 8%	3% - 5%
Voids filled with bitumen	65% - 72%	75% - 82%

Conclusion

- The design of asphalt mix is critical to the performance of the asphalt pavement, therefore the procedure for selecting the materials, proportioning them, and evaluating the mix to obtain the optimum binder content must be followed religiously.
- This will go a long way in ensuring that the road pavements are stable, durable, safe and provide a smooth ride to the users.

A stack of four sticky notes in yellow, orange, pink, and green is placed on a light blue background. A magnifying glass with a black handle and frame is positioned over the top left corner of the sticky notes. A black pen with a silver tip lies diagonally across the bottom right corner of the yellow sticky note. The text "Thank you For your Attention" is written in a black, cursive script on the yellow sticky note.

*Thank you
For your
Attention*